Comparison between theory and experimental measurements of the FNAL cooler

RHIC Electron Cooling Collaboration Workshop

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Introduction

- Mission of the Recycler Electron cooling: to provide an effective cooling tool for longitudinal cooling and storing of 8 GeV antiprotons in the Recycler ring

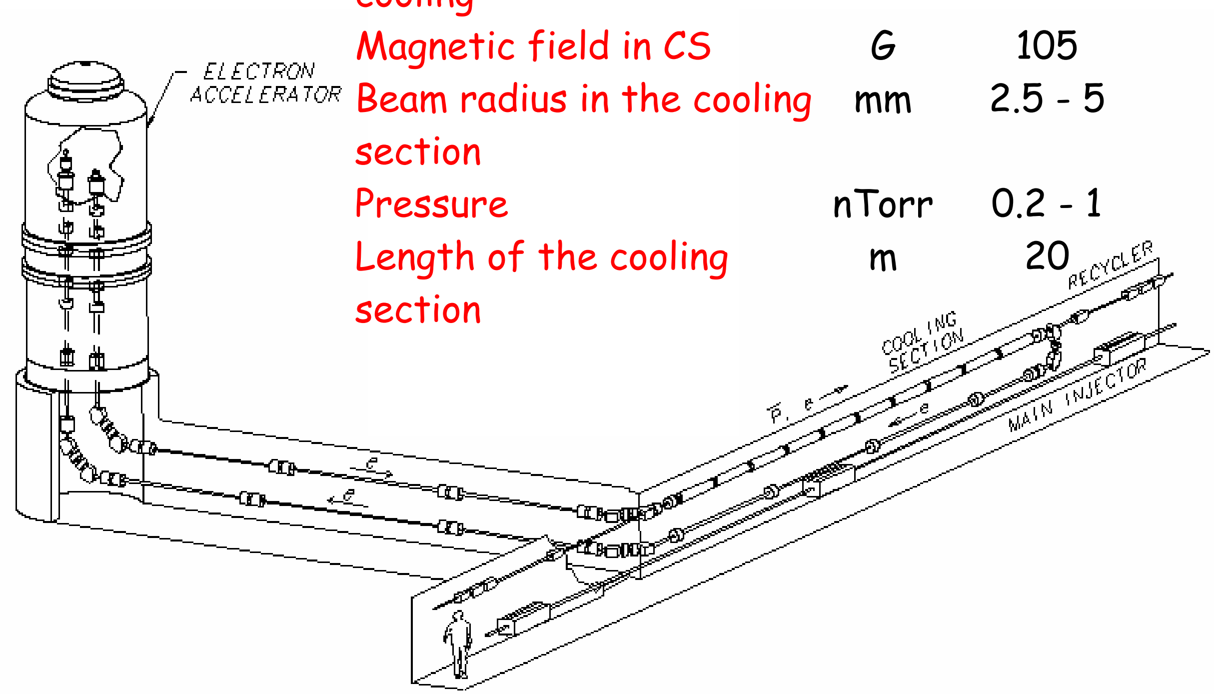
- The first cooling has been demonstrated in July 2005 and is routinely used in operation since then (see report of S. Nagaitsev).

- The detailed measurements were made only for the longitudinal cooling force

- This report compares results of the measurements with a non- magnetized formulae neglecting transverse motion of antiprotons.

Fermilab cooler – main features

Electron energy	MeV	4.338
Beam current used for cooling	A	0.05 - 0.5
Magnetic field in CS	G	105
Beam radius in the cooling section	mm	2.5 - 5
Pressure	nTorr	0.2 - 1
Length of the cooling section	m	20



- Electrostatic accelerator (Pelletron) working in the energy recovery mode
- DC electron beam
- 100 G longitudinal magnetic field in the cooling section
- Lamped focusing outside the cooling section

Electron beam parameters- longitudinal temperature

- The cooling process is determined by an effective energy spread consisting primarily of two components, the electron energy spread at a fixed time and the Pelletron voltage ripple
  - The energy spread is determined by IBS (the main contributor) and by density fluctuations at the cathode. According to simulations, at currents 0.1 – 0.5 A the energy spread is 70 – 150 eV.
  - The Pelletron voltage ripple is 200 - 300V r.m.s. (probably, fluctuates from day to day). The main frequency is 1.8 Hz, which is much shorter than a cooling time.
  - Hence, the effective energy spread is equal to these two effects added in quadratures.

Electron beam parameters- angles

Component	Present estimation, μrad	Diagnostics
Temperature	70	pepper pot image at OTR screen
Aberrations	50 ≤ 30	Simulated BPMs (at 1 mm)
Envelope scalloping	120*	Scrapers
Dipole motion caused by magnetic field imperfections	40	Magnetic measurements + BPMs
Beam motion	40	BPMs
Drift velocity	20**	Calculated (0.5 A beam with no secondary particles)
Total	**160*****	

*Measured for I = 0.5 A and averaged over the entire electron beam.

**There are indications that the drift velocity component might be dramatically (by ~20 times) underestimated

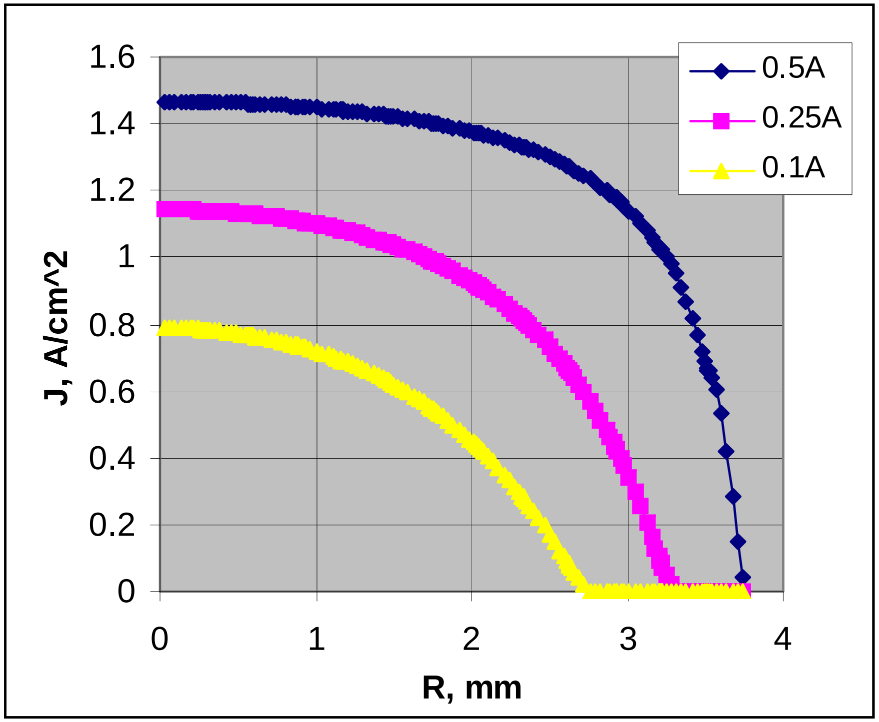
** Angles are added in quadratures

Electron beam parameters- current density

The beam envelope is nearly constant along the cooling section. Therefore, the currents density distribution replicates the distribution at the cathode,

$$j_{CS} = j_{cath} \times \frac{B_{CS}}{B_{cath}} \quad , \quad \frac{B_{CS}}{B_{cath}} = 1.2$$

However, the beam radius was measured equal to 4.5 mm instead of predicted 3.5 mm (at I = 0.5 A).



Current density distribution at the cathode simulated by SuperSAM code. Ua = 20 kV. Typical rms radius of the antiproton beam is 1 mm (for $\varepsilon_{n95\%} = 2\ \pi\ \mu m$).

Discrepancy with beam size measurements

- Two possible explanations of too large beam size measured in the cooling section with scrapers: a beam halo and secondary electrons
- Halo: the beam core behave very differently from a boundary portion (in these measurements, the beam boundary is determined by relative losses ~ 10^{-5})
  - Implication: current density is calculated from ratio of magnetic fields
- Secondary electrons: increase of the beam size can be explained by addition of a ~20% density of secondary (ionization) electrons kept by magnetic field and "clearing" voltage on BPMs
  - Current density is decreased by ~ 1.7 times
  - The main component of electron velocities outside of the axis is a drift

Velocities in the cooling section (beam frame)

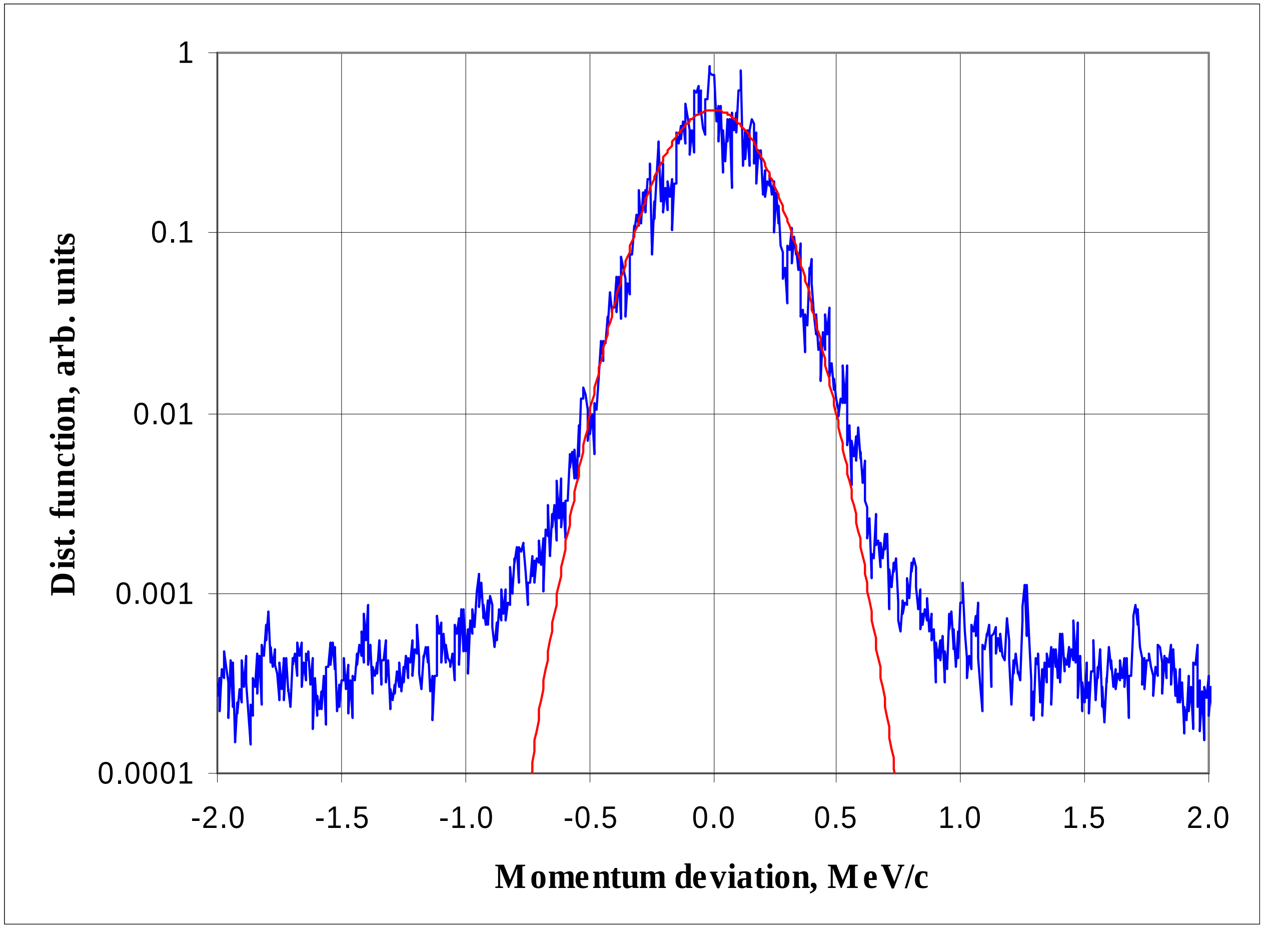
Source	Value in lab frame	R.m.s. velocity, 10^6 cm/s	Symbol
Effective energy spread in electron beam	300 eV	1.9	Ve_l
Electron angles in the cooling section	0.2 mrad	57	Ve_p
R.m.s. width of antiproton momentum distribution	0.2 MeV/c	0.67	Vp_l
Typical antiproton emittance, 95%, normalized	2 π mm mrad,	9.7	Vp_t
Antiproton energy offsets in voltage jump measurements	0.7 – 18 MeV/c	2.4 – 61	dVp

In the drag rate measurements $Ve_l \cdot \sqrt{\frac{m_e}{M_p}} << Vp_l < Ve_l << Vp_t << Ve_t$

Measurements of the longitudinal cooling force

- Special requirements:
  - Small number of pbars (1-5 × 10^{10})
  - Coasting beam
  - Narrow momentum distribution (< 0.2 MeV/c)
  - Low transverse emittances (< 3 π mm mrad, 95%, normalized)
- From equilibrium width (for small momentum offsets)
  - Reach equilibrium with e-cooling
  - Turn off e-cooling and measure the diffusion rate
- Voltage jump measurement
  - For momentum deviations > 1 MeV/c
  - Reach equilibrium with electron beam
  - Change electron beam energy
  - Record dynamics of the average pbar momentum

Longitudinal cooling force – example of measurement by equilibrium width



Longitudinal Shottky spectra of an antiproton beam in equilibrium.

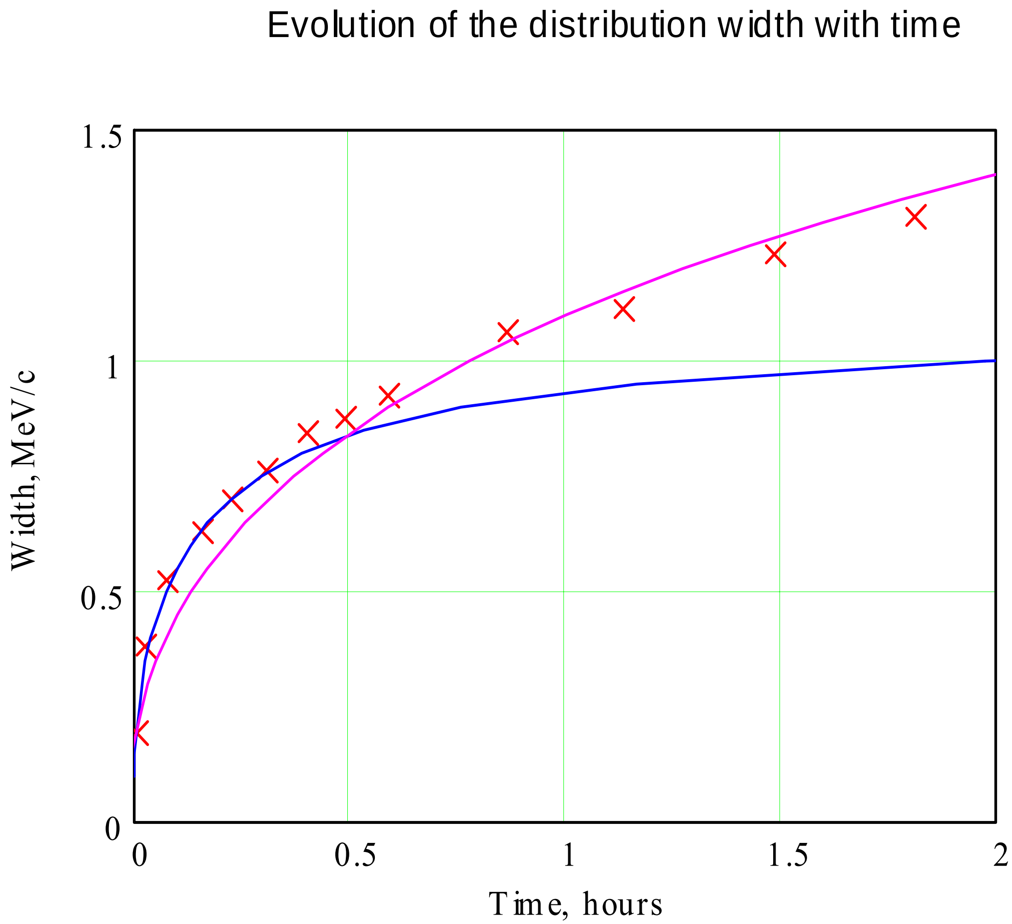
I=0.5A, e-beam on axis.

$\sigma_0 = 0.18$ MeV/c

$N_p=5\cdot10^{10}$

The r.m.s width of the equilibrium distribution σ_0 determines the derivative of the cooling force λ as $\lambda = \dfrac{D}{2\sigma^2}$ if the diffusion coefficient D is known.

Measurement of diffusion



Crosses are the data points; blue line is the best fit to first 6 points, D0 = 8.1 (MeV/c)2/h, σm=1.0 MeV/c;

magenta line shows diffusion with IBS calculated parameters D0 = 2.6 (MeV/c)2/h, σm=2.5 MeV/c

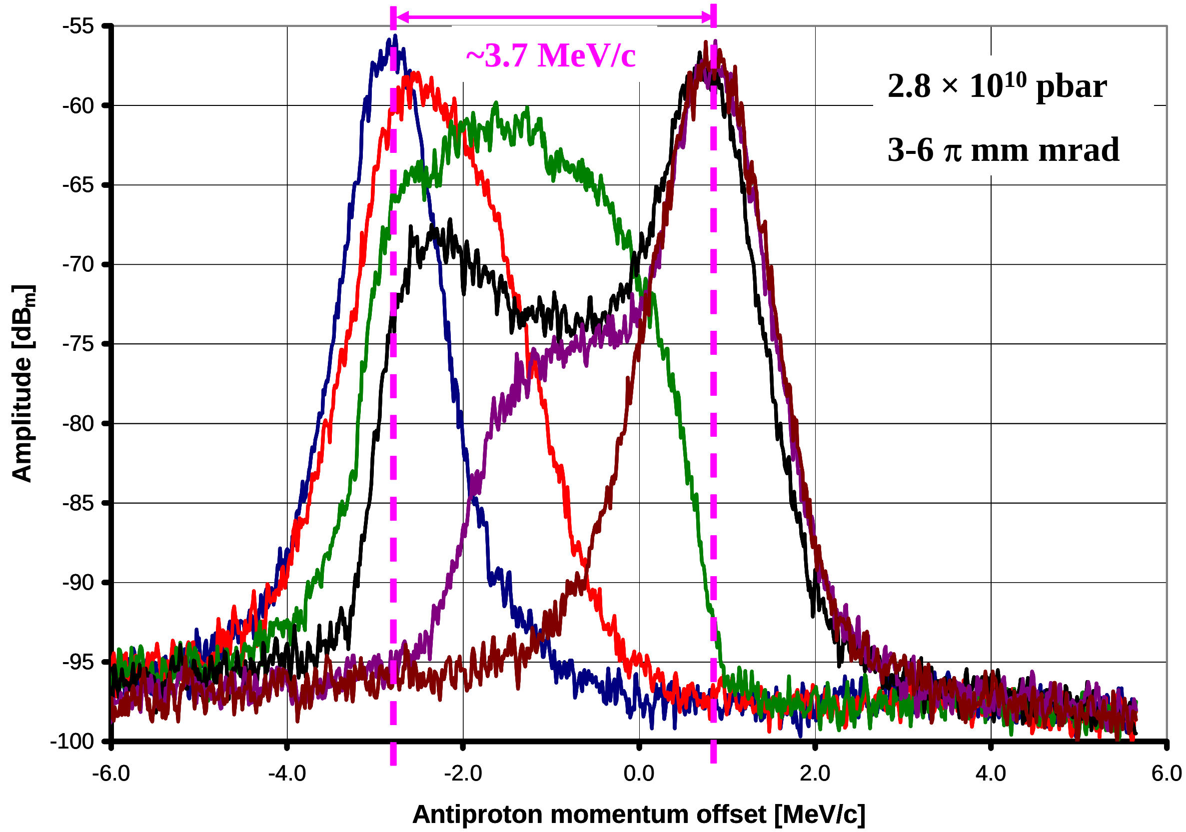
Fitting:

$$\frac{d}{dt}\sigma^2 = D_0\left(1 - \sqrt{\frac{\sigma}{\sigma_m}}\right)$$

N_p=3.5E10, ε = 1.5 π mm·mrad, σ_0 = 0.19 MeV/c.

λ= 30 hr^{-1} calculated from this diffusion is in a good agreement with fitting to the voltage jump data.

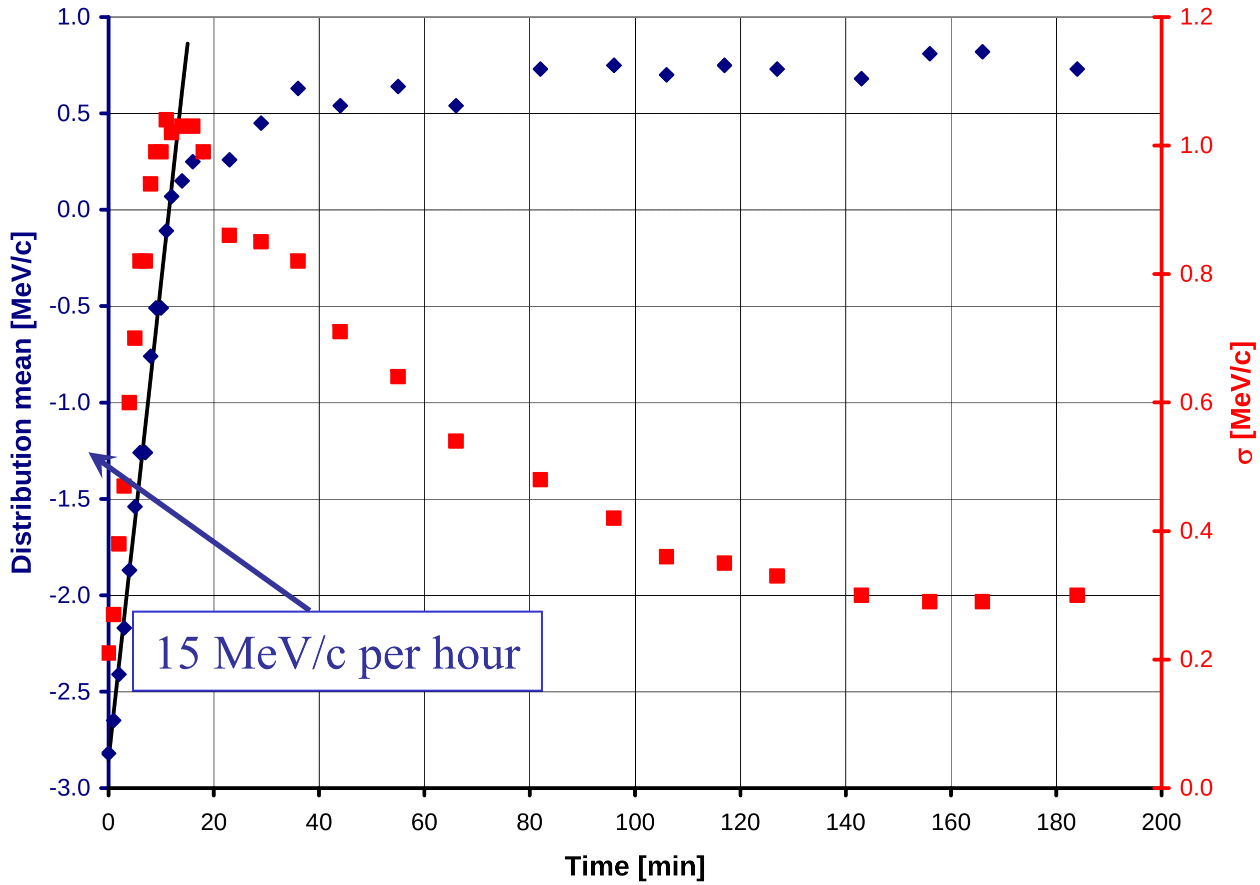
Longitudinal cooling force- example of a measurement by a voltage jump



Ie=0.5 A, electron beam is on axis, +2 kV jump (i.e. 3.67 MeV/c momentum offset). Zero MeV/c offset corresponds to the nominal Recycler energy.

Evolution of the antiproton momentum distribution as measured by a Schottky detector after a voltage jump. Traces (from left to right) are taken 0, 2, 5, 18, 96 and 202 minutes after the energy jump. Ie=0.5 A, electron beam is on axis, +2 kV jump (i.e. 3.67 MeV/c momentum offset).) Initial distribution. Other traces (from left to right) are taken 2 (b), 5 (c), 18 (d), 96 (e) and 202 (f) minutes after the energy jump.

Example of a measurement by a voltage jump (cont.)



Evolution of the weighted average and RMS momentum spread of the pbar momentum distribution function. The recorded cooling force is the initial derivative of the average. The program acquiring data was written by D. Broemmelsiek.

Non-magnetized model

Ve, Vp- velocities of an antiproton and electrons, Λ is Coulomb logarithm

$$\mathbf{F} = 4\pi n_e m \left(r_e c^2\right)^2 \Lambda \int_{-\infty}^{+\infty} f\left(\mathbf{v}_e\right) \frac{\mathbf{v}_e - \mathbf{v}_p}{\left|\mathbf{v}_e - \mathbf{v}_p\right|^3} \mathrm{d}^3\mathbf{v}_e$$

We assume a Gaussian distribution of the electron velocities with σ_z and σ_z standard deviations, and neglect transverse antiproton velocities.

$$f(\mathbf{v}_e) = \frac{1}{(2\pi)^{3/2}\sigma_\perp^2\sigma_\|} \exp\left[-\frac{v_{e\perp}^2}{2\sigma_\perp^2} - \frac{v_{e\|}^2}{2\sigma_\|^2}\right]$$

In simulations, the fitted parameters are the current density and r.m.s. values of the electron energy spread and angles.

$$\sigma_\perp = \beta\gamma\theta_e c$$

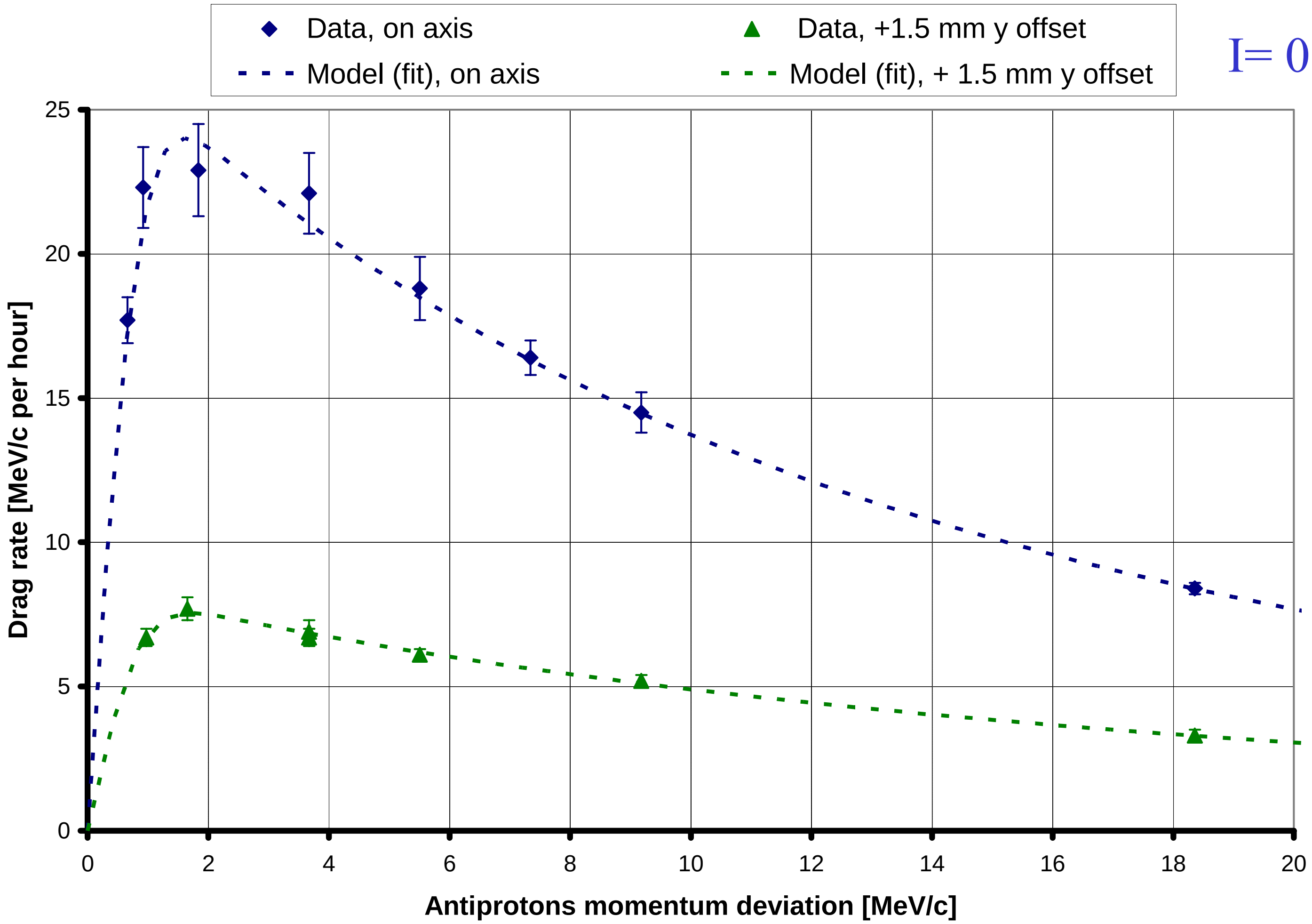
$$\sigma_{//} \approx \frac{\delta E}{\beta\gamma m c}$$

$$n_e = \frac{J_e}{\gamma e \beta c}$$

Lab frame quantities

Drag rate as a function of the antiproton momentum offset

I= 0.1 A



The drag rate measured on axis is consistent with calculations but at a radial offset drops faster than the simulated current density.

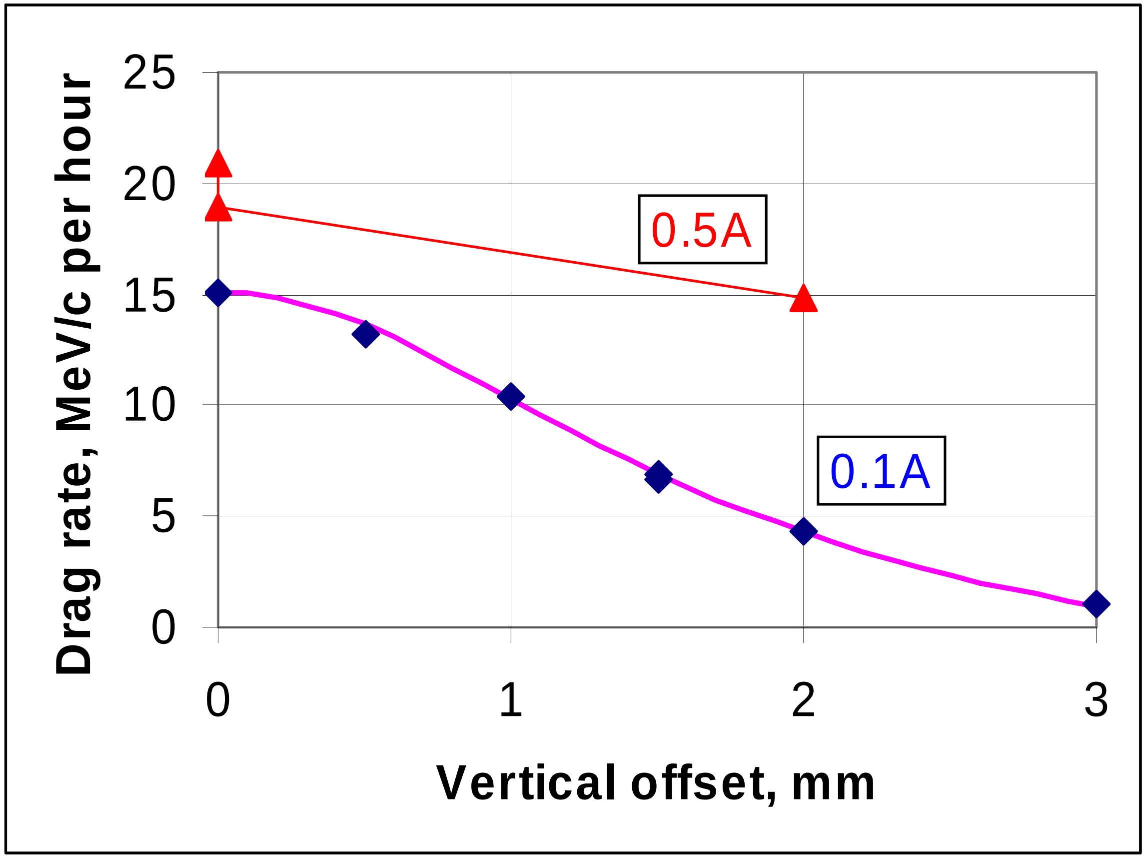
Fitted values

Offset,mm	0		1.5		2	
	Estimated	Fit	Estimated	Fit	Estimated	Fit
J_{cs}, A/cm^2	1/ 0.6	1.2	0.7/ 0.5	0.7	0.3/ 0.4	0.3
Θ_e, mrad	0.12/0.16	0.19	0.15/ 0.25	0.25	0.18/ 0.35	0.25
δE, eV	250	370	250	370	250	370

Comparison of values estimated from electron beam measurements with values from fitting the drag force curves (for three radial positions of the electron beam)

- The Coulomb logarithm is taken equal to 10
- Magenta numbers correspond to the model where a larger electron beam size, measured in CS with scrapers, is explained by a space charge of secondary electrons
- The effective energy spread was fitted at axis and used as a fixed parameter for off- axis curves (where the number of points was lower)

Radial dependence of the drag rate



Radial dependence of the drag rate for the beam current of 0.1 and 0.5 A. The voltage jump was 2 kV. The reason for a lowered on-axis drag rate in this set is unclear.

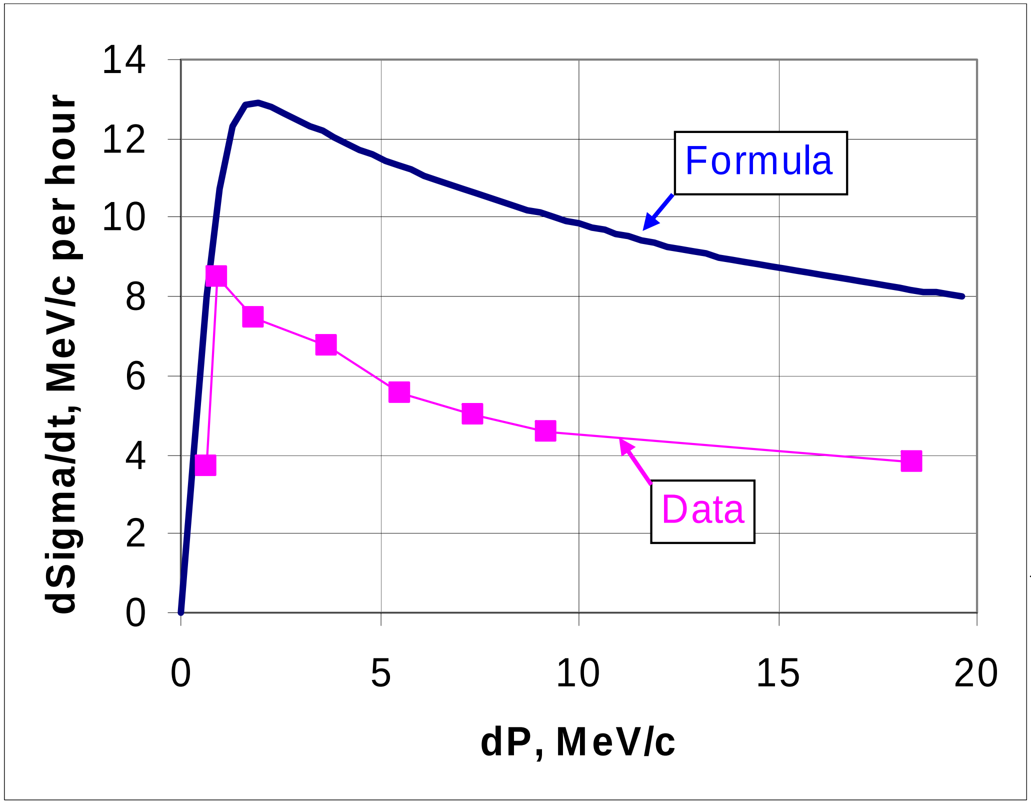
The magenta curve shows fit of 0.1 A data to

$$F(r) = F_0 \cdot \frac{1 - \dfrac{r^2}{r_m^2}}{1 + \dfrac{r^2}{r_1^2}}$$

with r_m= 3.5 mm, r_1= 1.7 mm.

r_m describes the density profile, and contribution of r_1 can be interpreted as an influence of the drift velocity

Widening of the distribution



Time derivative of the r.m.s. width of the longitudinal distribution as a function of the momentum offset. I = 0.1 A; e- beam is on axis.

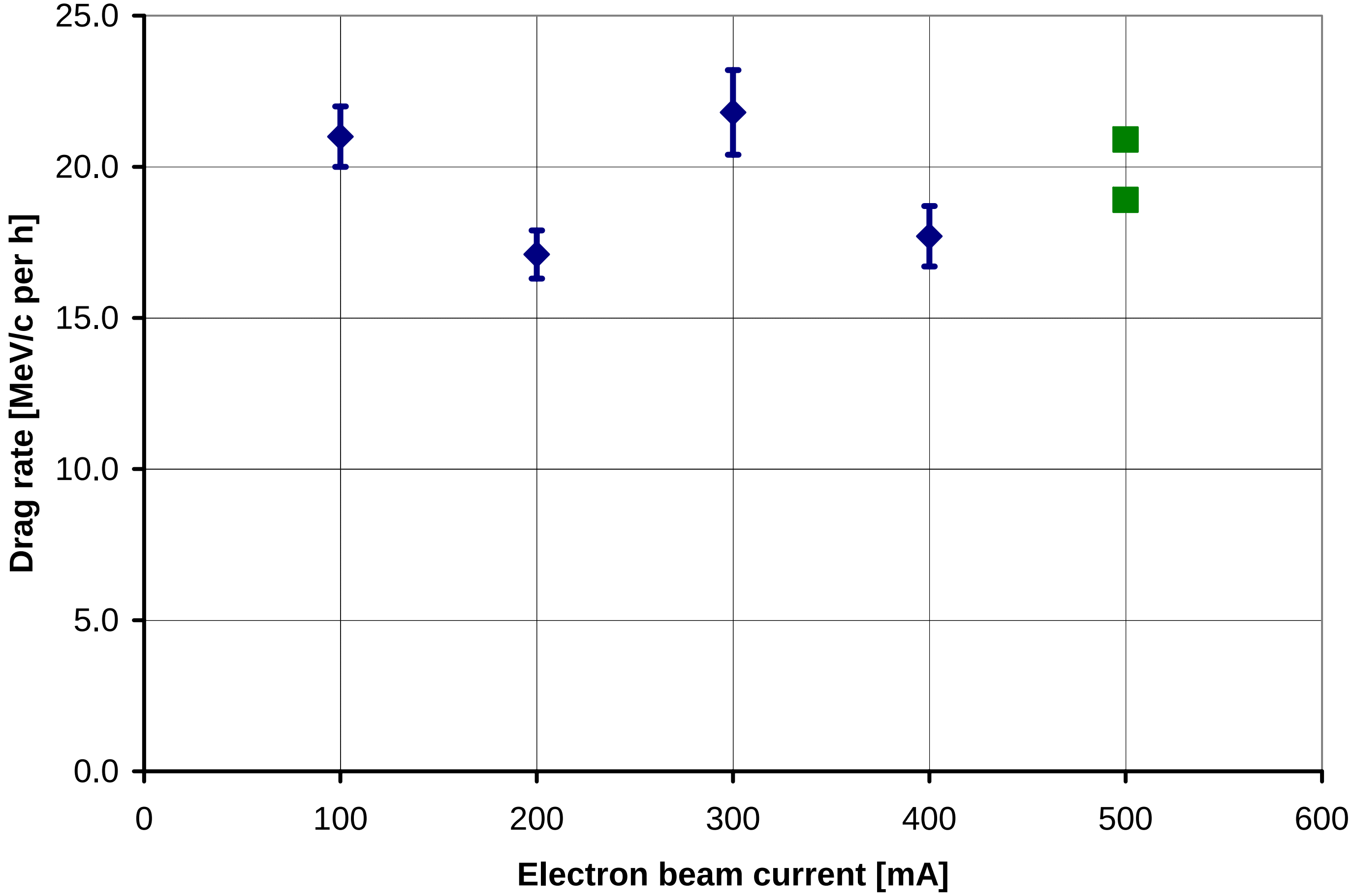
The blue curve is fitting to

$$\frac{d\sigma}{dt} = \frac{D}{2\sigma} - \frac{\partial F}{\partial p} \cdot \sigma - \frac{\partial F}{\partial (r^2)} \varepsilon \beta_{cs}$$

Drag force derivatives are calculated from corresponding fits.

Immediately after a voltage jump, the r.m.s. width of the distribution increases linearly with time. Reasons: diffusion, dependence of the drag force on the momentum offset and on transverse action of antiprotons.

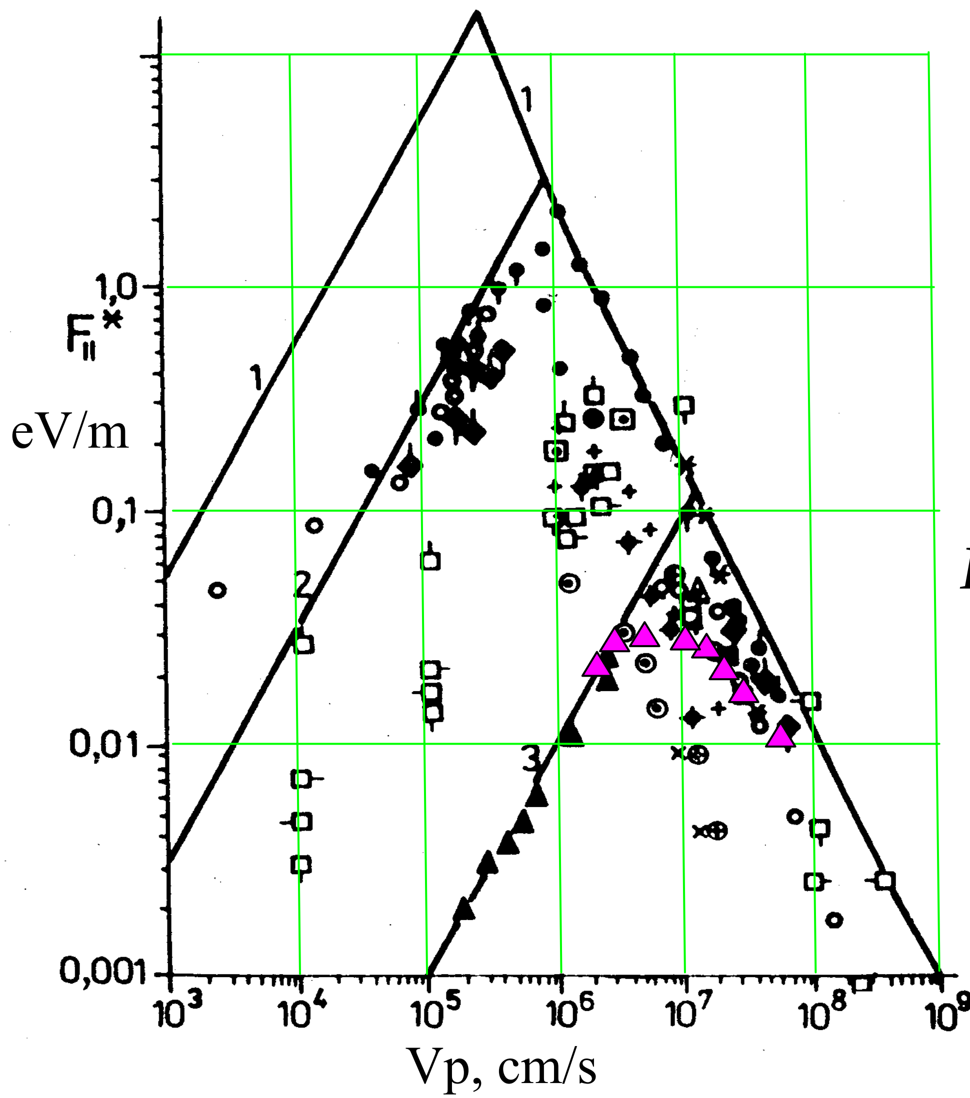
Drag rate as a function of the electron beam current



The voltage jump is 2 kV; electron beam is on axis.

The drag force is nearly constant at 0.1 – 0.5 A, while in simulations the current density at the axis is twice higher at 0.5 A than at 0.1 A.

Comparison with cooling force measured at low-energy coolers



Comparison with data for normalized longitudinal cooling force measured at low energy coolers adapted from

I.N. Meshkov, Phys. Part. Nucl., 25 (6), p. 631 (1994).

$$F^* = F_{||}/(10^{-8} cm^3 \cdot n_e \cdot \eta \cdot \gamma^{-1})$$

Red triangles represent Fermilab's data measured at 0.1 A. The current density is estimated in the model with secondary electrons.

Summary

- The drag rate was measured by an equilibrium width and by a voltage jump method and was compared with a non-magnetized formula.

- The data fit satisfactorily to the simulated curve with three fitting parameters (current density, electron angles, and the energy spread).

- The fitted parameters agree with the corresponding values estimated from measurements and simulations of the electron beam properties within ~ 50%. The main uncertainty seems to be in our knowledge of electron beam angles.